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Trow

COMPRESSIVE STRENGTH TEST PROCEDURES FOR TESTING HIGH STRENGTH CONCRETE

FINAL REPORT

by

TROW INC.

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1. INTRODUCTION

Standard methods for the testing of the compressive strength of concrete have been established for many years. However, in recent years, the use of mineral admixtures and high range water reducers has created possibilities for the production of concrete of a very high strength. This has raised the question as to whether current test procedures, which are based on experience with lower strength concretes, are applicable to the testing of high strength concrete.

High strength concrete has been used in Seattle, Chicago, Minneapolis, Toronto and other cities. A 96 MPa (14000 psi) mix was used for the 64-storey Society Centre in Minneapolis[1] and 225 W. Wacker Drive project in Chicago[2], 70 MPa mix in the 68-storey Scotia Plaza in Toronto[3] and an 85 MPa mix is currently being placed at the Bay-Adelaide Centre in Toronto. In the mock-up testing for the 58-storey Two Union Square in Seattle, maximum strength of concrete exceeded 145 MPa (21,000 psi) with an average of 132 MPa (19,100 psi)[1].

There are several aspects of the current standard compressive strength test that should be investigated to ensure an adequate test procedure for high strength concrete. These are mould type, specified test age and curing regime, machine stability and capacity, specimen size, preparation of the cylinder end surfaces and rate of load application.

This project investigated the effect of some of these factors, namely the methods of the preparation of the cylinder end surfaces, machine capacity, cylinder size and the rate of load application.

The end surfaces of concrete test cylinders, as cast, generally do not conform with the planeness and perpendicularity necessary for a precise compression test. The standard methods for the preparation of the end surfaces are described in ASTM C617[4] and CAN/CSA-A23.2-M90[5]. The most common method is capping with a sulphur mortar. In addition to capping with neat cement pastes or sulphur mortar, CAN/CSA-A23.2-M90[5] allows the use of grinding techniques to prepare the end surfaces. Another known method is the use of unbonded caps in an aluminum or steel restraining ring[6].

Most of the testing machines used by commercial concrete laboratories in North America, have a capacity of up to 2,000 kN, although this load produces a strength of 113 MPa using a 150 mm diameter cylinder it does not mean that it is suitable for concrete up to this

strength. The stability of the machine at this high load may be insufficient and could lead to eccentric loading.

The use of specimens of a smaller diameter than the standard 150 mm test cylinders would help in alleviating this specific problem with the testing machines. It would also facilitate the handling of the specimens and decrease the space necessary for curing.

The rate of loading specified by the current standards[4, 5] was established for lower classes of concrete. It is not known what effect the two rate of loading extremes have on the strength of high strength concrete.

The investigation was carried out during the period of January-August, 1990.

2. OBJECTIVES

The objectives of this investigation were:

i) to determine the relative performance of 6 test cylinder end preparation techniques in the compressive strength test. The techniques were: sulphur capping, grinding, grinding and capping, sawing and capping, and unbonded caps in aluminum restraining rings using cylinders with ground and untreated ends. Cylinders of 70 and 90 MPa class concrete were used in the tests.

ii) to determine the effect of a standard capacity (2000 kN) and high capacity (4,500 kN) compression machines on the compressive strength of 100 mm and 150 mm diameter cylinders.

iii) to determine the effect of the cylinder size on the measured strength and test variability using 100 mm and 150 mm diameter cylinders of 50, 70 and 90 MPa class concrete.

iv) to establish the effect of the rate of loading of 100 mm and 150 mm diameter cylinders on their strength using 70 and 90 MPa class of concrete. Three rate of loadings, all complying with the current standards, were to be tested.

The above testing was carried out with the objective of producing recommendations for the amendment of current standards with regards to the testing of high strength concrete.

3. TESTING MACHINES

Two testing machines were used to evaluate the various cylinder end finishing techniques. One of the machines (No. 1) was the 2000 kN ELE machine at the Trow Inc. laboratory in Brampton and the other a 4500 kN MTS machine (No. 2) at the University of Toronto.

Both machines had been recently calibrated, No. 1 to within ±1% on March 2, 1990 and No. 2 to within ± 0.2% on May 30, 1989.

Shortly before starting the tests the two machines were compared by the University of Toronto using a 3000 kN load cell. The results of this comparison are given in Tables A and B and shown graphically in Figure 6.

It was found that up to approximately 600 kN Machine 1 (Trow) produced lower load than Machine 2 by up to approximately 0.6%. Over 600 kN it produced higher load than Machine 2 by up to approximately 0.8%.

4. FABRICATION AND CURING OF TEST CYLINDERS

To facilitate the evaluation of the various cylinder end finishing techniques and the monitoring of the strength development prior to testing, a total of 80 - 150 mm diameter and 40 - 100 mm diameter cylinders were fabricated for each of the two classes of concrete. Ready mixed concrete was used for these tests. When the truck arrived at the laboratory with a 2 m^3 load, it discharged approximately 0.5 m^3 into a waste bin before filling 5 wheel barrows to their capacity (Photo 1). Sixteen large and 8 small cylinders were made from the concrete in each wheel barrow. Two technicians were assigned to each wheel barrow, one of whom placed the concrete in the moulds while the other compacted it. The standard method of casting specimens[7] was employed. Immediately after casting the cylinders were placed in a standard moist room. The next day they were demoulded, marked for identification and placed in a lime saturated water at normal laboratory room temperature where they remained until their testing.

The evaluation of the effect of cylinder size and the rate of loading (and the monitoring of the strength development prior to testing) involved a smaller number of cylinders so the concrete batches were prepared in a laboratory pan type mixer using the same materials and mix proportions as used in the ready mixed concrete. Twelve large and 18 small cylinders were cast

from each batch for the evaluation of the effect of the cylinder size, while 17 large and 4 small (or 20 small and 9 large) specimens were cast for the determination of the effect of the rate of loading. The casting procedures and curing were the same as for the ready mixed concrete.

Heavy duty plastic moulds having a wall thickness of 6 mm (1/4") were used throughout the test program.

The mix proportions and the test results obtained on the fresh concretes are shown in Table C.

5. CYLINDER END PREPARATION

Sulphur capping was carried out in accordance with CAN/CSA-A23.2-9C[5]. The capping compound was a high strength commercial sulphur mortar. Its strength, as tested in compliance with the above CSA Standard[5], was 54.7 MPa at 2 h and 70.8 MPa at 24 h. Each cap was checked for voids, planeness, and perpendicularity. All specimens were capped one day prior to compression testing.

The lapping (grinding) of the cylinder ends was performed using a machine equipped with a rotating-oscillating diamond disk and an automatic specimen movement device (Photos 2 and 3). Each cylinder end was checked for planeness and perpendicularity as required by CAN/CSA A23.2-9C[5].

The cutting of the cylinder ends was with a diamond blade saw. The lapped and capped as well as the cut and capped cylinder ends were checked for compliance with the void, planeness and perpendicularity requirements (Photo 4).

If any of the capped, lapped, lapped and capped or cut and capped cylinder ends did not comply with the planeness or perpendicularity (and void in the case of capped ends) requirements, treatment was repeated until compliance was achieved.

The unbonded caps were 13 mm thick neoprene pads in an aluminum restraining ring (Photo 5). The pads used in the first tests were of 55 Shore A hardness. Because of the problems described later, a set of 60 Shore A hardness pads was obtained since it was thought that the harder pads would perform satisfactorily.

6. EFFECT OF THE VARIOUS END PREPARATION METHODS ON STRENGTH AND VARIABILITY (PHASE I)

Two sets of cylinders were tested. One of them was tested by Trow (Machine No. 1) and the other by the University of Toronto (Machine No. 2). All cylinders were cured and their ends prepared by Trow. The set of specimens tested by the University of Toronto was delivered to the University on the day before the testing and stored there in a standard moisture room. The Trow set was stored in the same manner. Each set consisted of 5 cylinders selected at random (one originating from each wheel barrow) and one extra cylinder (also selected at random) for contingency.

The test results obtained on the standard cylinders (Part A) are shown in Table D-1 and those obtained on the 100 mm diameter cylinders (Part B) in Table D-2. They are also presented graphically in Figures 1 to 4. When any of the 5 cylinders did not produce a satisfactory form of break or when a defect was found or was suspected, the test result was rejected and substituted with the test results obtained on the contingency cylinder. When there was no improper form of break or no defective cylinder in the set, the strength of the contingency cylinder was not included in the evaluation. In a few cases contingency cylinders were not available.

As stated earlier, the two machines were compared by the University of Toronto using a load cell. In the load range used in this phase Machine No. 1 produced higher load (approximately 0.3% for the 70 MPa concrete and 0.4% for the 90 MPa concrete). This is considered to be an insignificant difference.

It is evident from the test data (Table D-1) that in all cases, with one exception, Machine No. 1 (Trow) produced higher strength than Machine No. 2 (U of T) by 4 - 7%. The exception was the lapped 90 MPa cylinders whose strength produced by either machine was approximately the same. Since cylinders for the tests by the two laboratories were selected at random and in each case great care was taken to ensure that the specimens were properly centered in the machine in order to avoid eccentric loading, no firm explanation is offered for the differences produced by the two machines. The consistency of these differences suggests that the cause is due to the machine characteristics rather than test procedures.

If the low test result (79.2 MPa) obtained on a sulphur capped 90 MPa cylinder by Machine 2 is rejected, it will be clear that both the sulphur capping method and the lapping method produce consistent test results with the maximum coefficient of variation for Machine 1 being 1.72% (90 MPa concrete, lapped ends) and for Machine 2 being 1.77% (90 MPa concrete, sulphur caps). Sulphur capped cylinder must be handled with great care to avoid damage to the caps and a greater care is required to center it in the machine because of the caps being of larger diameter than the cylinder. This, in addition to the many things that can go wrong during the capping process, such as incorrect cap thickness or other flaws and weaknesses in the cap itself, due to material or procedural deficiencies, makes the lapping method more practical.

It is important to note that in this test program, all procedures were closely supervised by an experienced Professional Engineer. The low variability of the sulphur capped cylinder test results reflects this close supervision. In normal routine testing this level of supervision is not normally possible and significantly higher variability occurs.

For two sets of specimens, the upper platen of Machine No. 2 was fixed in a horizontal position to allow comparison of strength results under fixed and fully free platen condition. Only lapped cylinders were tested in this fashion.

The fixing of the platen did not have a negative effect on the strength. When the spherical head of the machine was fixed the strength was approximately 0.7% higher in the case of 70 MPa concrete and 2.5% higher in the case of 90 MPa concrete than when the head was free to move. The coefficients of variation for the two conditions did not differ significantly.

The lapping and capping, and the cutting and capping of the ends did not produce significantly different or less variable test results than the capping or the lapping alone. Due to this and the increased cost of either of the two methods there is no justification for recommending either of these options.

The use of restraining rings and neoprene pads created serious problems. Under load, the neoprene was extruded from the cylinder ends and filled the space between the cylinder and the restraining ring. This jammed the cylinder making it difficult to remove the fractured concrete from the rings. The jamming (restraint) caused a shear failure at the level of the top of the rim of the rings (Photo 6) which extended from the periphery of the cylinder to approximately 30 - 50 mm towards the center. The University of Toronto could not test this group of cylinders for the

above reasons, and also because the neoprene pads were being forced out of the restraining rings. Trow (Machine 1) was able to carry out the test, however the strength obtained was somewhat lower than the strength of the lapped or the capped cylinders tested normally. The variation in the strength was considerably higher for the 70 MPa concrete and somewhat lower for the 90 MPa concrete, compared to either sulphur caps or lapping. The hardness of the neoprene pads in the case of the 70 MPa concrete was 55 Shore A. It was felt that the use of a harder pad would eliminate the jamming problem and the 70 MPa concrete test was repeated using 60 Shore A pads. No improvement was evident. The 90 MPa concrete was tested using the 60 Shore A pads. If this technique is to be considered further for high strength concrete, pads of much higher hardness values should be investigated.

On the basis of the above tests (Phase I, Part A), the lapping method was selected as the most practical and least variable. Part B of Phase I involved the determination of the relative performance of the selected method and the sulphur capping method using 100 mm diameter, 200 mm long cylinders. The test results are shown in Table D-2 for 70 MPa and 90 MPa concrete. It is evident from the test data that Machine 1 (Trow) produced significantly greater variation in the test results than Machine 2 (U of T). The diameter of the bearing face of the spherically seated block was 165 mm in both machines, and complied with the ASTM C39-86 requirement for the standard (150 mm) and 100 mm diameter cylinders. During the test program it was observed that the bolts fixing the block in Machine 1 slackened frequently and required regular tightening. It is possible that this caused eccentric loading, resulting in the larger strength variation. Both machines produced less variation and higher strength values in the case of the lapped than the sulphur capped cylinder ends. Machine 1 produced strengths higher by approximately 3 - 5% than Machine 2 in the case of the 90 MPa concrete. However, the results were reversed in the case of the 70 MPa concrete. This was due to the higher variation and several low test results for the latter concrete.

For the load range in question the machine comparison (Figure 6) indicates negligible machine difference for the 70 MPa concrete and approximately 0.3% difference for the 90 MPa concrete. Machine difference should therefore have insignificant effect on the test results.

7. EFFECT OF CYLINDER SIZE ON STRENGTH AND VARIABILITY (PHASE II)

This phase of the test program involved the comparison testing of the standard (150 x 300 mm) and 100 x 200 mm cylinders at various strength levels. The original program

called for the use of 3 classes of concrete - 50, 70 and 90 MPa. However, the lowest class produced strengths higher than the required level and two additional batches were therefore made to provide a strength range of approximately 40 to 100 MPa. In addition to the strength tests, each cylinder was tested for its saturated surface dry density using the water displacement method.

To address the slackening of the spherical head of the compression machine, (Machine 1 only was used), the head was returned to the manufacturer's representative for modification. Rubber shock absorbers were inserted into the platen block and the modification virtually eliminated the problem.

The ends of all cylinders were prepared by the lapping method and each was checked for and complied with the standard requirements for planeness and perpendicularity.

The test results are shown in Table E-1 and E-2 and Figure 5. As in Phase I, there were also contingency cylinders in Phase II. The program called for 10 cylinders of each size. Two extra cylinders were tested and their test results were used if a test result was rejected due to an unsatisfactory form of break or a defect in the specimen.

It is evident from Table E-1 that there was only an insignificant variation in the densities of the large as well as the small cylinders. Except in the case of the 50 MPa mix B where the mean density of the large and small cylinders was the same and in the case of the 50 MPa mix C where the mean density of the large cylinders was higher than that of the small cylinders, the mean density of the small cylinders was higher than that of the large. However, the maximum difference was only 13 kg/m^3 and the compaction of the large and the small cylinders was therefore considered to be the same and the small differences were not expected to have any significant effect on the compressive strength.

In each case the small cylinders produced a higher mean strength than the large. The ratio of the small to large cylinder strengths was the lowest for the weakest mix (50 MPa mix A, approximately 42 MPa) and the strongest mix (90 MPa, approximately 98 MPa). These ratios were 1.003 and 1.018, respectively. The strength ratio for the other three mixes ranging in strength from approximately 60 to 84 MPa, was 1.037 to 1.042. The ratio for the highest strength cylinders is considered to be less reliable due to the high variation in strength experienced with these cylinders. In the case of the large cylinders the testing machine exerted loads close to 85% of

its capacity. This overloading of the machine and possibly also the explosive nature of the failure occurring with each test are considered to be responsible for the high variation in the test results.

Other investigators [2, 8, 9, 10, 11] have also reported that the small cylinders produce higher strength test results. Some [8, 9, 11] report that this difference increases with an increase in the strength level and one states[10] that the difference is insignificant or that the small cylinders tend to produce slightly lower strength [12]. This investigation deals only with concretes in the 40 - 100 MPa strength range, using test cylinders with the ends ground plain as opposed to sulphur mortar capped ends and shows that the small cylinders produce higher strength by up to 4.2 percent.

The variation in the strength of the small cylinders was comparable to or lower than that of the large cylinders. This contrasts with the findings of other investigators [2, 8] one [2] of whom dealt with 83 MPa concrete and the other [8] with 7 to 42 MPa concretes.

Of particular significance is the general increase in the standard deviation and coefficient of variation with an increase in strength level regardless of specimen size. Machine characteristics appear to be the main contributing factor.

8. EFFECT OF RATE OF LOADING ON STRENGTH (Phase III)

The effect of the rate of loading was determined on the two sizes of test cylinders using the slowest and the fastest rate allowed by the test standard [5] plus the routine procedure of very fast loading rate (0.70 MPa/sec.) up to 50% of the total anticipated load followed by 0.25 MPa/sec. The test results are shown in Table F.

As expected the strength increased with the increase in the rate of loading. The lowest rate (0.15 MPa/sec.) produced approximately 2-3% lower and the highest allowable rate (0.35 MPa/sec.) up to 1.6% higher strength than the "routine rate" regardless of the test cylinder size. As in Phase II (Table E-2), the 90 MPa concrete test results varied more than the lower strength test results, especially where the standard (150 mm diameter) test cylinder was used.

9. CONCLUSIONS

The following conclusions can be drawn from the tests described above:

- (Phase I)

a) the most reliable of the six cylinder end finishing methods is the lapping method. Although an insufficient number of tests were carried out to state firmly that this method produces less variable test results for all conditions than the sulphur cap method, it is more practical because

(i) grinding does not require dry cylinder ends,
(ii) it is less susceptible to operator variables and errors,
(iii) each sulphur cap must be checked for bond and thickness requirements,
(iv) working with molten sulphur can be hazardous to safety and health,
(v) sulphur caps damage easily,
(vi) sulphur capped cylinders require more time than lapped ones to position them properly in the machine.

The measured strength of the lapped cylinders was generally the same as the strength of the capped cylinders.

b) The lapped and capped and cut and capped cylinders did not produce significantly different or less variable test results than the lapped only cylinders.

c) The use of the neoprene pads in the restraining rings method produced unreliable test results because of the jamming of the cylinders in the rings and the horizontal shear failure plane at the level of the top of the ring.

d) The strength of 100 x 200 mm cylinders with lapped ends was consistently less variable and somewhat higher than with the sulphur capped ends.

e) Machine 2 (4500 kN) produced generally somewhat lower and less variable strengths than Machine 1 (2000 kN). The effect of the fixing of the upper platen of Machine 2 was a slightly higher strength and no significant change in the strength variability.

- (Phase II)
  The strength of lapped 100 x 200 mm cylinders was 1.8 to 4.2% higher than that of lapped 150 x 300 mm cylinders in the range of approximately 58-97 MPa. The variability of the strength of the large cylinders was comparable to or higher than that of the small cylinders. There was practically no difference in the strength and variability when the strength was approximately 42 MPa.

- (Phases II and III)
  The Phase II and III tests, where only Machine 1 was used, showed clearly that the variability of the strength test results was higher for the 90 MPa class concrete than for the lower strength concrete. This emphasizes the influence of test machine characteristics as concrete strength level increases.

- (Phase III)
  The strength values obtained at the lowest rate of loading was approximately 1.9-2.8% lower, and the strength obtained with the highest rate of loading allowed by the test standard [5] was up to 1.6% higher, than that obtained with the routine rate of loading, i.e. a very fast rate (0.70 MPa/sec) up to 50% of the maximum load followed by the average rate allowed by the standard. This applied to both the large and the small cylinders.

10. RECOMMENDATIONS

10.1 Procedures

It is recommended that the lapping method be specified for the preparation of the ends of high strength concrete test cylinders and that the ends be required to comply with the requirements of the CSA test standards[5] for planeness and perpendicularity. It is also recommended that 100 x 200 mm cylinders be allowed with no change in the number of specimens constituting one test. However, the use of the small test cylinder should be limited to high strength concretes with a nominal aggregate size not larger than 14 mm until the effect of the larger size aggregates is determined.

10.2 Further Research

(1) The influence of aggregate size and shape on strength values and variability should be investigated for the 100 mm diameter specimens

(2) Since test machine characteristics appear to be an important influencing factor in the higher within test variability for the higher strengths of concrete, further investigation is necessary to define test machine requirements.

(3) Round robin tests to assess the suitability of a range of machines in current use should be undertaken to verify the findings of (2).

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TABLE A

Load Calibration of Machine 2

University of Toronto
4500 kN MTS Test Machine
(March 8, 1990)

MTS		Load cell		% Error*
voltage (V)	load (kN)	voltage (V)	load (kN)	
1.000	250.0	1.006	251.5	-0.596
2.002	500.5	2.013	503.3	-0.546
3.000	750.0	3.010	752.5	-0.332
4.003	1000.8	4.009	1002.3	-0.150
5.000	1250.0	5.002	1250.5	-0.040
6.000	1500.0	5.994	1498.5	+0.100
6.999	1749.8	6.983	1745.8	-0.229
8.001	2000.3	7.975	1993.8	-0.326

* Assuming the load cell is correct

TABLE B

Load Calibration of Machine 1

Trow Inc.
ELE Autotest 450, 2000 kN Test Machine
(March 6, 1990)

ELE load (kN)	Load cell Run #1		Run #2		Avg. % Error*
	V	kN	V	kN	
200.0	0.804	201.0	0.806	201.5	-0.621%
400.0	1.618	404.5	1.620	405.0	-1.174%
800.0	3.194	798.5	3.194	798.5	+0.188%
1200.0	4.786	1197.0	4.786	1197.0	+0.251%
1500.0	5.976	1494.0	-	-	+0.402%
1800.0	7.170	1793.0	7.167	1792.0	+0.418%
2000.0	7.960	1990.0	7.957	1989.0	+0.528%

* Assuming the load cell is correct

TABLE C

Mix Proportions and Fresh Concrete Test Results

Mix Description	Ready Mixed Concrete Phase I		Laboratory Mixed Concrete Phase II					Phase III			
	70 MPa	90 MPa	50 MPa A	50 MPa B	50 MPa C	70 MPa	90 MPa	70 MPa*	90 MPa*	70 MPa**	90 MPa**
Mix Proportions , kg/m³											
Cement	315	335	241	241	241	315	335	315	335	315	335
Slag	117	125	90	90	90	117	125	117	125	117	125
Silica Fume	38	40	19	29	29	38	40	38	40	38	40
Coarse Aggr. (10mm)	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Fine Aggr.	715	695	830	820	820	715	695	715	695	715	695
Retarding WR	893	950	684	684	684	893	950	893	950	893	950
Water	145	145	141	145	145	145	145	145	145	145	145
HRWR	6110	6500	4680	4680	4680	6110	6500	6110	6500	6110	6500
Fresh Concrete Test Results											
Immediately after Discharge											
Slump, mm	240	215	180	220	230	210	160	190	130	220	190
Air Content, %	1.2	1.3	1.4	1.3	2.0	1.5	2.0	1.5	2.0	1.3	1.8
Density, kg/m³	2475	2475	2503	2468	2472	2484	2475	2475	2461	2468	2485
Immediately after casting cylinders											
Slump, mm	180	100									
Air Content, %	1.4	1.8									
Density, kg/m³	2494	2475									

* Test cylinders - 150 mm diameter
** Test cylinders - 100 mm diameter

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TABLE D-1

COMPRESSION TEST RESULTS, PHASE I, PART A

150 MM DIAMETER CYLINDERS

End Preparation Method	70 MPa Concrete		90 MPa Concrete	
	Machine 1	Machine 2	Machine 1	Machine 2
Sulphur Caps	71.7*	74.8	90.1	83.9
	78.2 x= 76.8	74.7 x= 74.3	90.0 x= 90.3	79.2 x= 84.1
	77.1 Sx= 1.07	72.1 Sx= 1.25	92.0 Sx= 1.06	85.4 Sx= 3.04
	75.2 v= 1.40	73.3* v= 1.68	89.1 v= 1.17	84.6 v= 3.61
	76.8	74.7	90.1	87.4
	76.9	75.2		
Lap	78.6 x= 77.4	74.1 x= 74.0	88.5	88.5
	77.4 Sx= 1.11	74.4 Sx= 0.88	88.7 x= 90.0	90.6 x= 90.3
	76.0 v= 1.43	72.8 v= 1.18	89.9 Sx= 1.55	90.7 Sx= 1.21
	76.7	73.5	90.6 v= 1.72	91.8 v= 1.34
	78.4	75.1	80.2*	90.0
	77.1*	75.2*	92.3	87.6*
		Upper Platen Fixed		Upper Platen Fixed
		69.5* x= 74.5		94.0
		75.1 Sx= 1.19		91.7 x= 92.6
		72.6 v= 1.60		92.1 Sx= 1.00
		74.3		79.2* v= 1.09
		75.7		92.5
		75.0		N.T.
Lap and Cap	58.2* x= 75.1		90.5	88.9
	78.7 Sx= 3.94		92.0 x= 92.3	89.6 x= 88.5
	74.8 v= 5.24		94.4 Sx= 1.39	86.2 Sx= 1.34
	72.4		92.4 v= 1.51	89.2 v= 1.51
	79.3		87.6*	88.7
	70.2		92.3	
Cut and Cap	79.8 x= 77.7		91.9	82.9
	73.6 Sx= 2.44		91.6 x= 91.3	90.7 x= 86.0
	77.8 v= 3.15		90.7 Sx= 1.49	87.2 Sx= 3.70
	79.2		93.2 v= 1.63	83.2 v= 4.30
	78.3		89.2	N.T.
	77.0*		90.3*	
Restraining Ring Lap	77.4 x= 75.8		88.6	
	73.8 Sx= 1.79		89.4 x= 88.8	
	73.9 v= 2.36	N.T.	90.0 Sx= 0.95	N.T.
	77.5		88.5 v= 1.07	
	76.7		87.5	
	77.0*		90.7*	
Restraining Ring Untreated	75.4 x= 74.1		88.5	
	73.3 Sx= 2.23	N.T.	88.8 x= 88.0	
	72.4 v= 3.01		87.6 Sx= 0.85	N.T.
	72.0		88.4 v= 0.97	
	77.3		80.7*	
	76.0*		86.7	

Age of test cylinders - 70 MPa 24d, 90 MPa 42d N.T. - not tested

x= mean strength, Sx= standard deviation, v= coeff. of variation

* - Result not included in analysis (see text, page 5, par. 2)

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TABLE D-2

TEST RESULTS, PHASE I, PART B

100 MM DIAMETER CYLINDERS

End Preparation Method	70 MPa Concrete		90 MPa Concrete	
	Machine 1	Machine 2	Machine 1	Machine 2
Sulphur Caps	65.5 77.2 x= 71.0 64.9 Sx= 5.52 74.7 v= 7.78 71.3* 72.5	75.6 76.8 x= 74.7 73.0 Sx= 1.52 73.9 v= 2.03 74.0	95.1 87.1 x= 90.9 90.6 Sx= 2.84 90.7 v= 3.12 91.0 95.4*	84.6 88.8 x= 86.6 85.7 Sx= 2.04 88.7 v= 2.35 85.0 87.5*
Lap	74.4 x= 73.6 76.6 Sx= 3.96 66.7 v= 5.38 75.6 74.8 73.7*	76.5 x= 76.0 76.5 Sx= 0.93 76.6 v= 1.22 76.1 74.4 75.2*	95.0 98.1 x= 95.0 76.5* Sx= 2.26 83.3* v= 2.38 92.7 94.3	90.7 93.4 x= 91.8 92.3 Sx= 1.04 91.4 v= 1.13 91.4

Age of test cylinders - 70 MPa 24 d, 90 MPa 42d

* - Result not included in analysis (see text, page 5, par. 2)

TABLE E-1

SSD Density Test Results
Phase II

Cylinder No.	Mix No.									
	50 MPa A		50 MPa B		50 MPa C		70 Mpa		90 MPa	
	Diameter of Test Cylinder, mm									
	100	150	100	150	100	150	100	150	100	150
	SSD Density, kg/m^3									
1	2484	2480	2478	2481	2469	2481	2473	2474	2485	2473
2	2489	2482	2480	2484	2475	2482	2482	2468	2486	2473
3	2491	2483	2480	2483	2469	2482	2484	2463	2482	2474
4	2485	2482	2482	2479	2484	2486	2478	2466	2486	2470
5	2488	2478	2479	2476	2477	2484	2483	2469	2487	2477
6	2487	2479	2478	2478	2480	2479	2481	2463	2487	2469
7	2493	2484	2481	2480	2476	2480	2479	2470	2486	2474
8	2489	2479	2481	2478	2469	2482	2479	2466	2487	2474
9	2492	2485	2481	2482	2479	2484	2480	2466	2484	2471
10	2487	2481	2482	2478	2476	2484	2476	2465	2486	2476
11	2493	2482	2478	2476	2477	2483	2472	2466	2488	2475
12	2489	2476	2485	2484	2481	2478	2485	2467	2493	2477
All Specimens										
x	2489	2481	2480	2480	2476	2482	2479	2467	2486	2474
Sx	2.94	2.61	2.07	2.87	4.90	2.31	4.10	3.06	2.61	2.57
v	0.12	0.11	0.08	0.12	0.20	0.09	0.17	0.12	0.10	0.10
Without Specimen Nos.	11 and 12	11 and 12	11 and 12	11 and 12	11 and 12	1 and 12	11 and 12	11 and 12	7 and 11	1 and 8
x	2488	2481	2480	2480	2475	2483	2480	2467	2486	2474
Sx	2.92	2.31	1.48	2.56	5.10	2.07	3.31	3.37	2.83	2.84
v	0.12	0.09	0.06	0.10	0.21	0.08	0.13	0.14	0.11	0.11

TABLE E-2

Compressive Strength Test Results
Phase II, Machine 1

Cylinder No.	Mix No.									
	50 MPa A		50 MPa B		50 MPa C		70 Mpa		90 MPa	
	Diameter of Test Cylinder, mm									
	100	150	100	150	100	150	100	150	100	150
	Compressive Strength, MPa									
1	42.4	41.6	60.1	57.5	68.5	62.3	86.3	83.0	95.4	82.4
2	42.2	42.4	60.8	58.5	68.2	65.7	83.7	80.0	100.3	94.6
3	42.0	42.4	60.6	59.1	68.2	65.9	85.2	83.0	101.0	97.4
4	42.7	41.7	60.9	58.1	68.3	65.5	81.6	81.5	100.1	98.9
5	42.6	42.1	61.4	58.9	69.0	66.7	83.5	81.5	94.2	93.7
6	41.6	41.9	61.2	57.7	68.7	66.5	86.0	79.8	100.2	101.0
7	42.6	42.4	59.6	59.2	68.2	67.0	85.3	79.4	88.3	96.9
8	43.0	42.8	60.6	58.3	68.4	65.2	84.9	81.4	97.1	88.7
9	42.3	42.5	60.9	58.0	68.6	65.4	83.6	82.5	99.9	89.6
10	42.2	42.5	60.2	56.3	68.7	64.7	86.0	83.0	95.9	95.1
11	42.6	42.3	61.0	57.0	69.3	67.6	83.8	82.6	82.8	99.1
12	42.1	41.5	61.8	56.5	67.1	67.1	84.8	82.6	97.8	98.7
All Specimens										
x	42.36	42.18	60.76	57.93	68.43	65.80	84.56	81.69	96.08	94.68
Sx	0.373	0.411	0.598	0.964	0.540	1.406	1.363	1.324	5.516	5.388
v	0.88	0.98	0.98	1.66	0.79	2.14	1.61	1.62	5.74	5.69
Without Specimen Nos.	11 and 12	11 and 12	11 and 12	11 and 12	11 and 12	1 and 12	11 and 12	11 and 12	7 and 11	1 and 8
x	42.36	42.23	60.63	58.16	68.48	66.02	84.61	81.51	98.19	96.50
Sx	0.395	0.389	0.540	0.868	0.270	0.903	1.482	1.387	2.432	3.327
v	0.93	0.92	0.89	1.49	0.39	1.37	1.75	1.70	2.48	3.45
Strength Ratio (100/150)	1.003		1.042		1.037		1.038		1.018	
Age of concrete (days)	4		5		16		17		43	

TABLE F

Rate of Loading Test Results
Phase III, Machine 1

Cylinder No.	100 x 200 mm Cylinders						150 x 300 mm Cylinders					
	70 MPa Mix			90 MPa Mix			70 MPa Mix			90 MPa Mix		
	Rate of Loading, MPa/sec						Rate of Leading, MPa/sec					
	0.15	0.35	50% 0.70 50% 0.25	0.15	0.35	50% 0.70 50% 0.25	0.15	0.35	50% 0.70 50% 0.25	0.15	0.35	50% 0.70 50% 0.25
	Compressive Strength, MPa											
1	75.5	77.7	77.6	68.4	91.2	91.7	75.3	76.5	77.6	96.6	99.8	94.6
2	75.5	77.1	77.4	91.3	95.0	93.4	75.6	77.2	78.2	93.3	94.7	92.7
3	75.8	77.1	77.8	90.3	93.5	93.5	75.9	76.7	78.3	92.0	99.6	99.2
4	74.5	78.3	77.9	91.0	92.0	91.3	75.1	78.2	75.9	95.9	99.6	98.3
5	76.0	78.1	77.4	88.0	94.2	92.5	76.2	77.9	75.7	96.3	97.2	98.5
6	76.6	78.5	78.4	92.7	94.8	93.2	71.3		74.3			90.2
All Specimens												
x	75.65	77.80	77.75	86.95	93.45	92.60	74.90	77.30	76.67	94.22	98.18	95.58
Sx	0.695	0.603	0.378	9.218	1.546	0.930	1.808	0.738	1.613	2.049	2.221	3.667
v	0.92	0.78	0.49	10.60	1.65	1.00	2.41	0.96	2.10	2.16	2.26	3.84
Without Specimen No.	6	6	6	1	1	6	6	-	6	-	-	6
x	75.46	77.66	77.62	90.66	93.45	92.48	75.62	77.30	77.14	94.82	98.18	96.66
Sx	0.577	0.555	0.228	1.724	1.546	0.986	0.444	0.738	1.254	2.049	2.221	2.848
v	0.76	0.71	0.29	1.90	1.65	1.07	0.59	0.96	1.63	2.16	2.26	2.95
Strength Ratio	0.972	1.001	1.000	0.980	1.010	1.000	0.980	1.002	1.000	0.981	1.016	1.000
Age of Concrete (days)	8			27			12			36		

Key: x - Mean
Sx- Standard Deviation
v - Coefficient of Variation

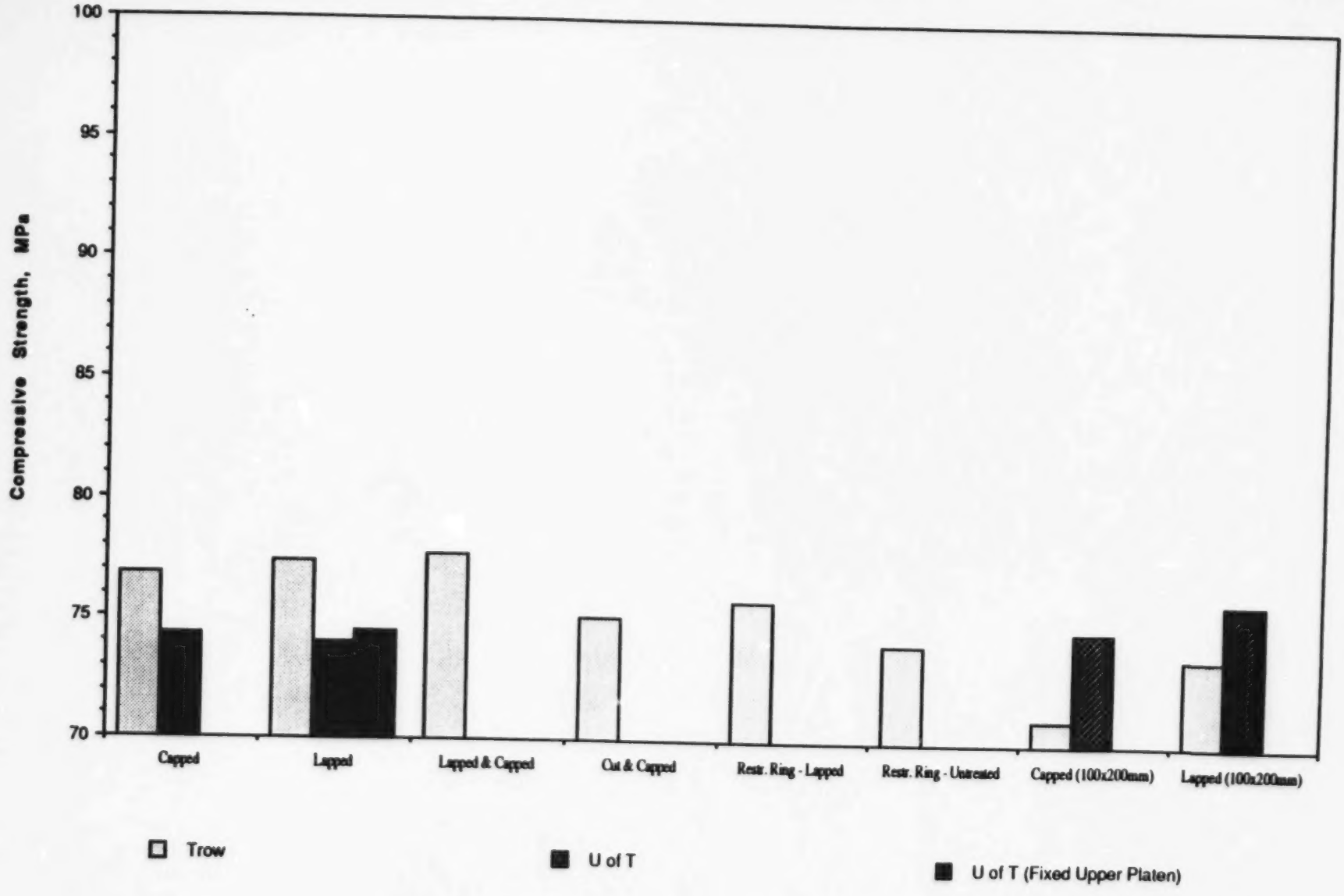


Fig. 1. Compressive Strength, 70 MPa.
(Standard Cylinders Unless Otherwise Stated)

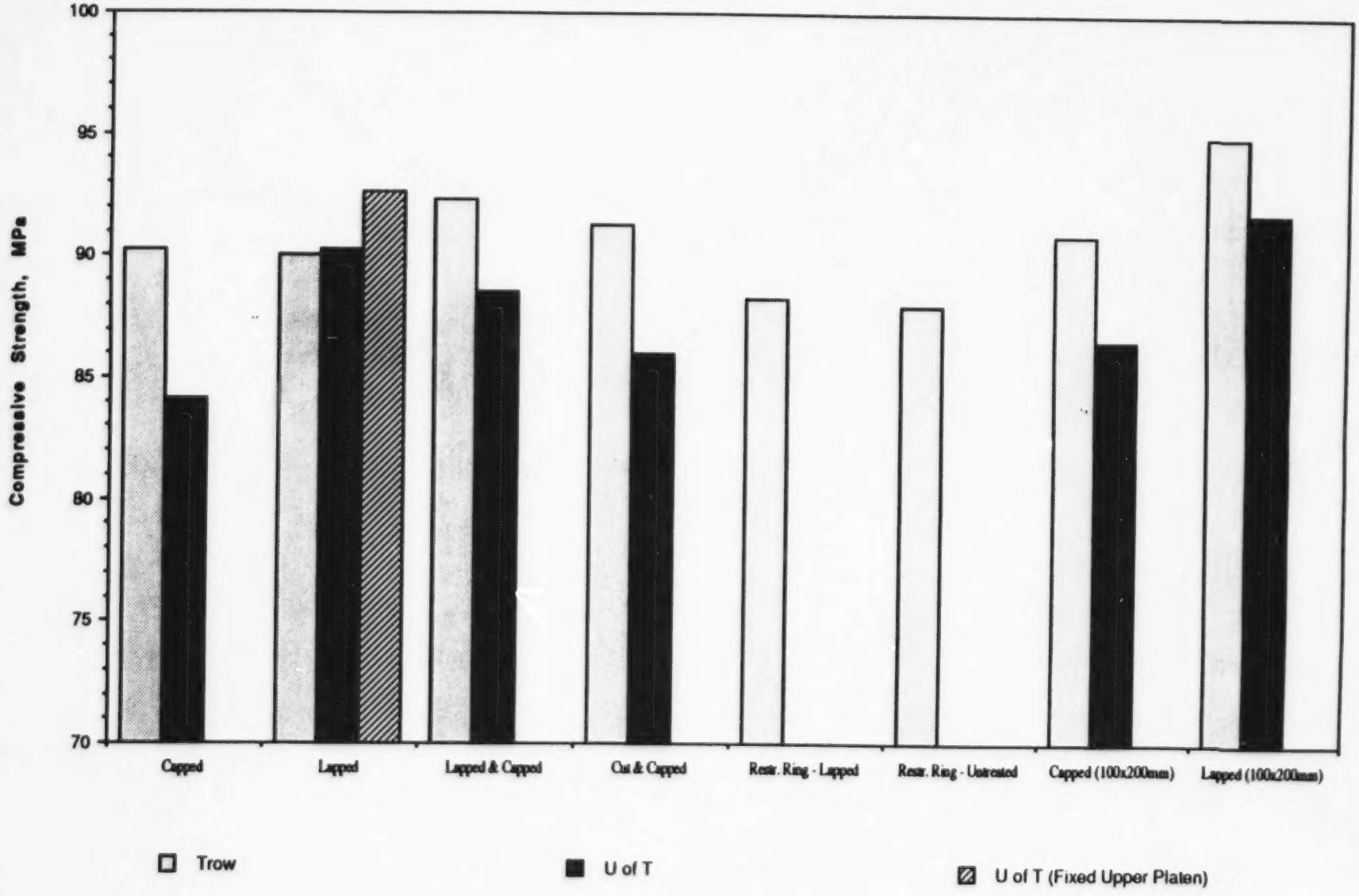


Fig. 2. Compressive Strength, 90 MPa.
(Standard Cylinders Unless Otherwise Stated)

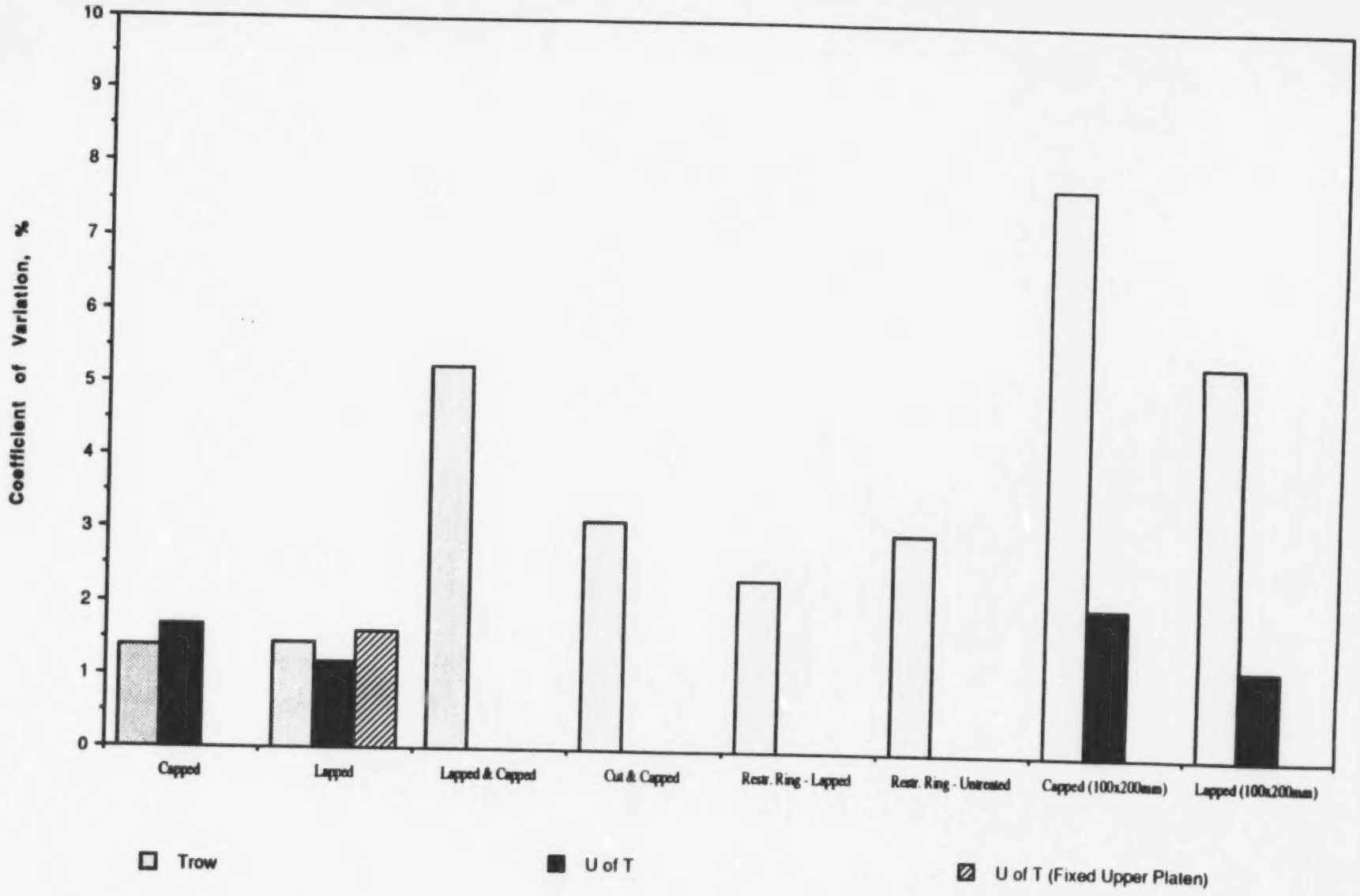


Fig. 3. Variation in Strength, 70 MPa.
(Standard Cylinders Unless Otherwise Stated)

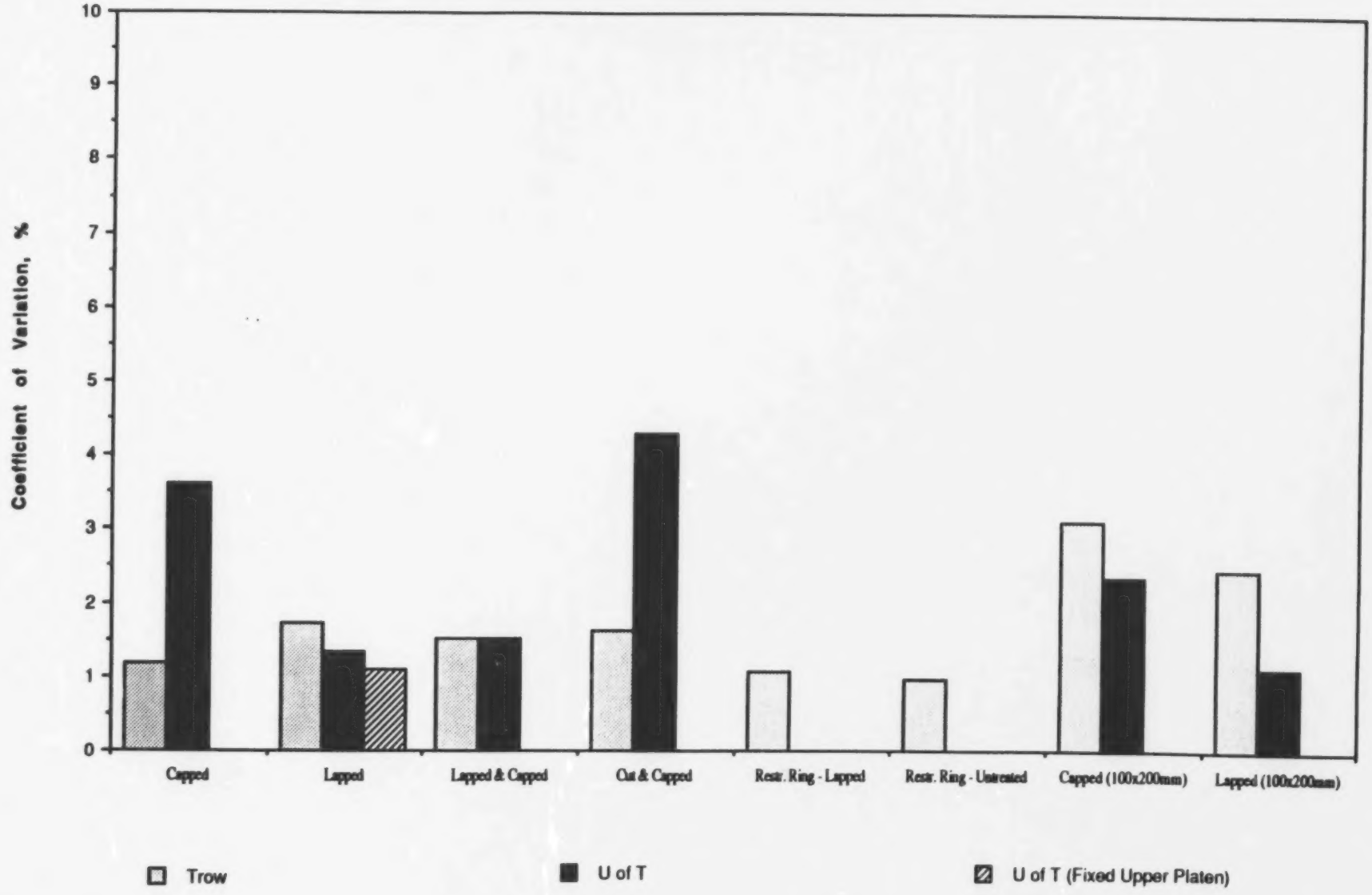
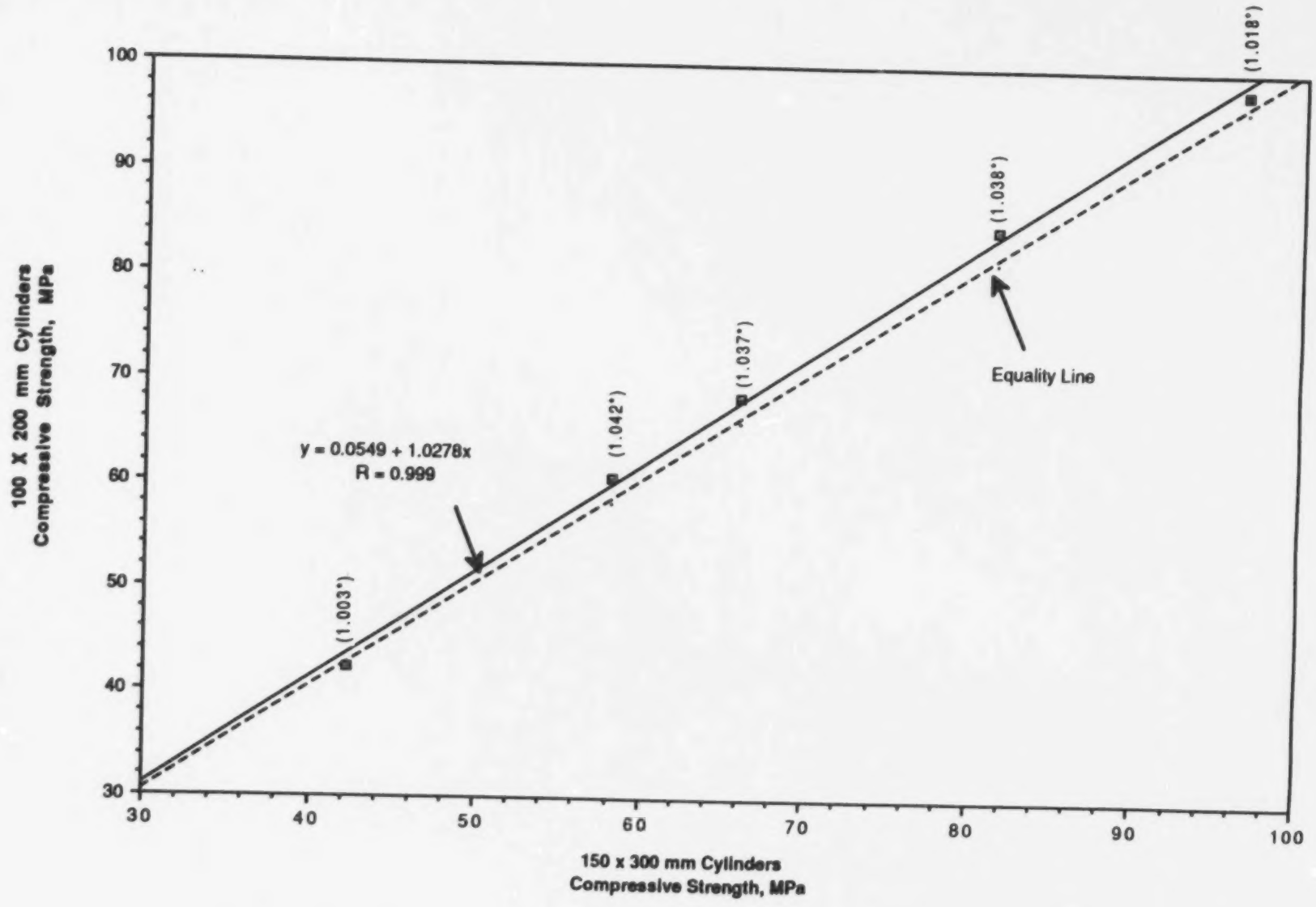


Fig. 4. Variation in Strength, 90 MPa.
(Standard Cylinders Unless Otherwise Stated)

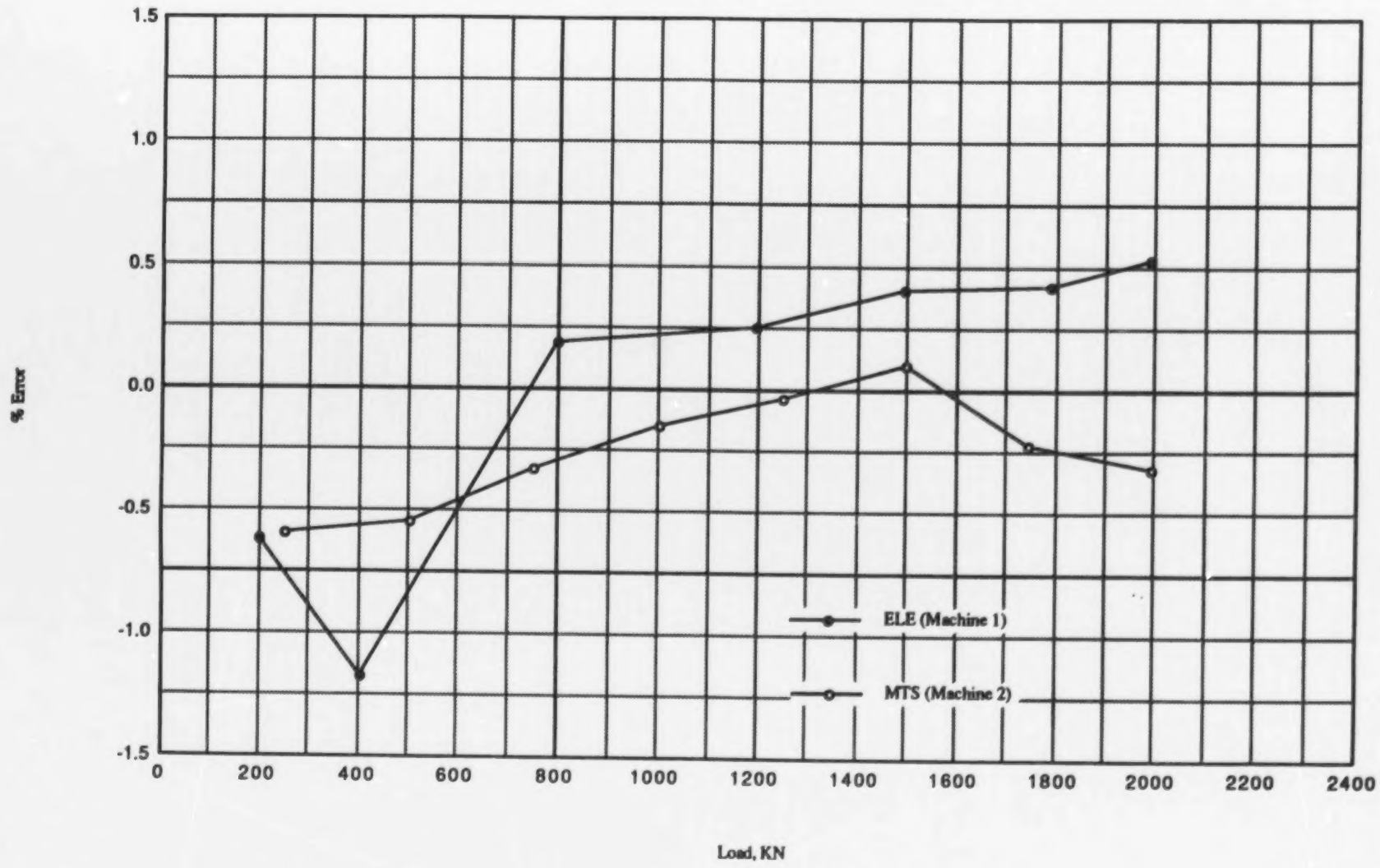


* Strength Ratio (100mm Cyl./150mm Cyl.)

Fig. 5 - Effect of Cylinder size on Compressive Strength

Load Cell Comparison of ELE and MTS Machines

Figure 6



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Trow

Photograph No. 1

Discharging concrete into a wheelbarrow

Photograph No. 2

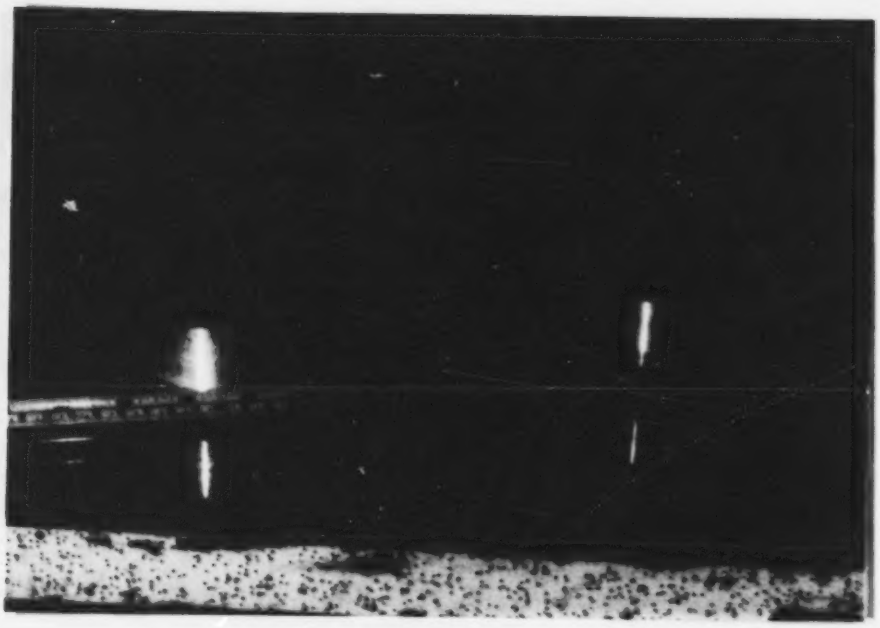
Specimen end grinding machine

Photograph No. 3

Specimen end grinding machine (grinding device)

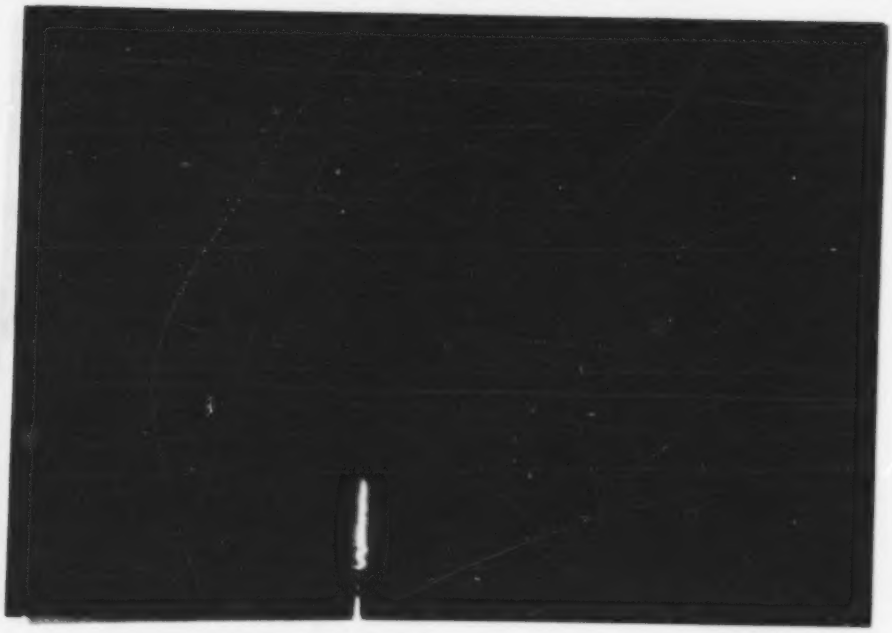
Photograph No. 4

Checking capped cylinder for perpendicularity



Photograph No. 5

Restraining rings and rubber pads



Photograph No. 6

Shear failure of cylinder tested in the restraining rings